# Properties of Magnetic Tunnel Junction bits for MRAM


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# Outline

## Background

## Reading from an array of MTJ bits

- opportunities

## Writing bits in an array

- opportunities

## Summary

# MRAM Attributes

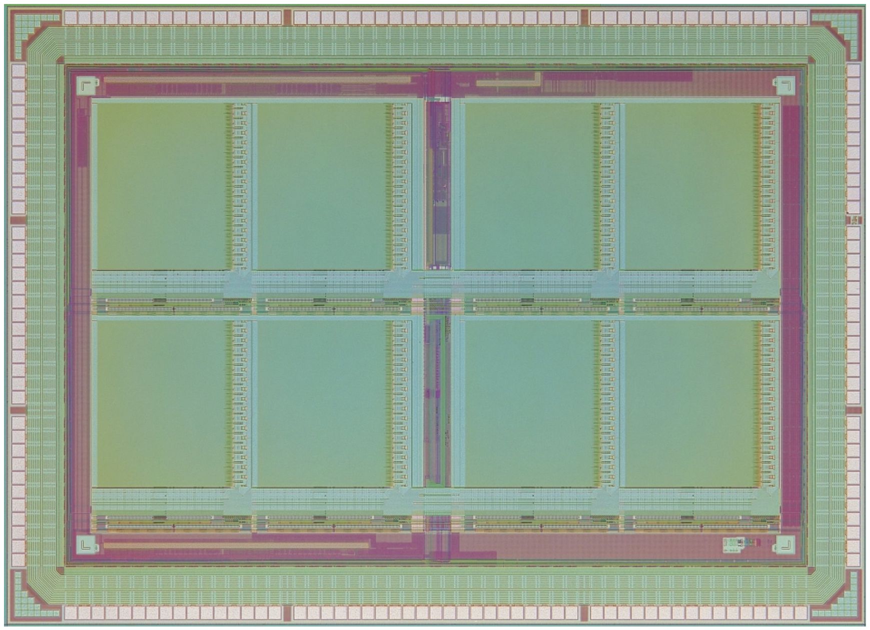
MRAM offers multiple memory capabilities that are currently realized by separate memories: *universal memory*

Non-Volatility **with fast programming, no program endurance limitation**

Random Access **with no refresh.**

Non-destructive read

# 4Mb MRAM Circuit



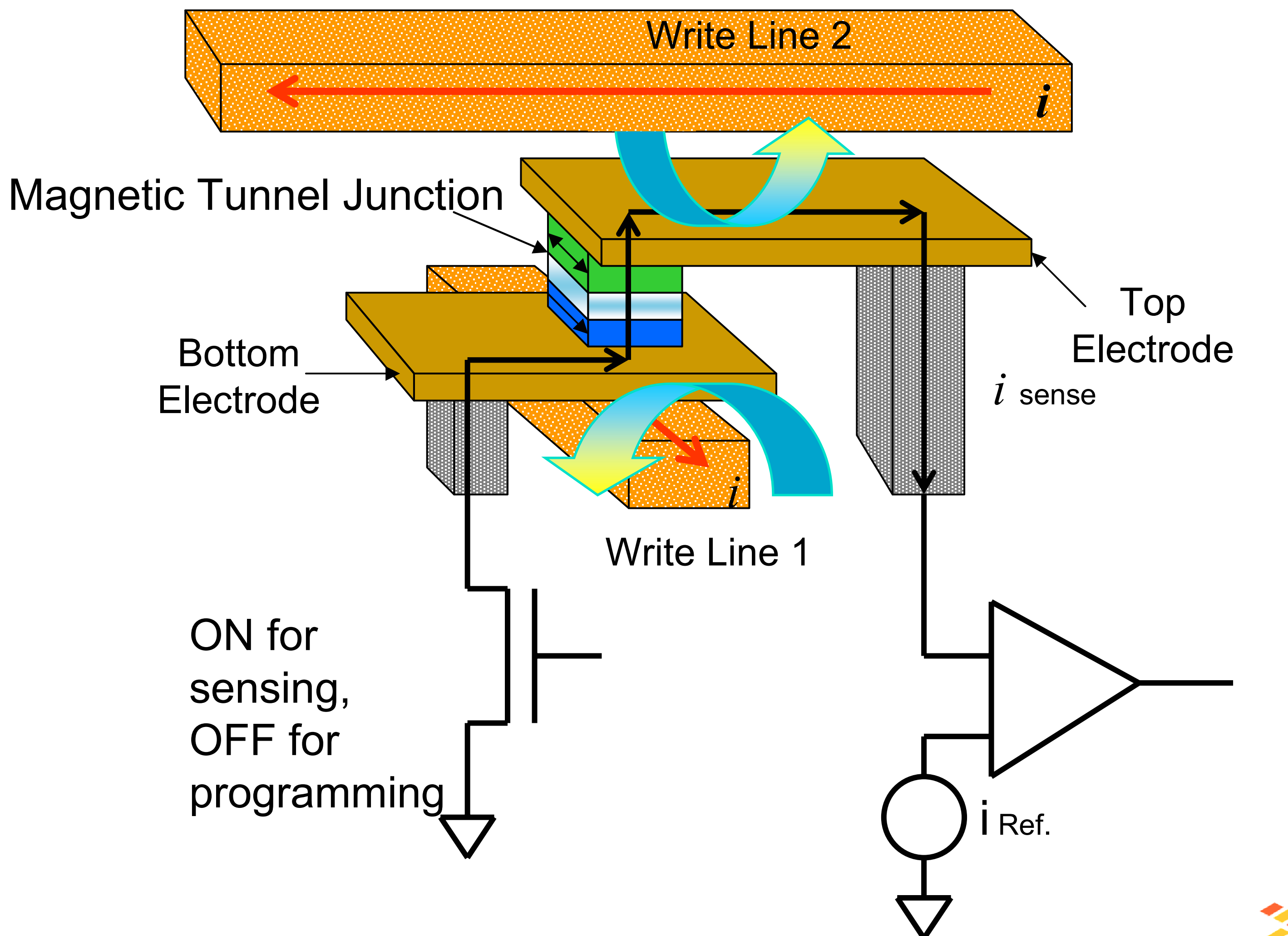
4Mb MRAM die

- 0.18µm CMOS with 3 layers of Aluminum and 2 layers of Copper Interconnects
- Cladded write lines
- 256K x16 Organization
- 3.3V Supply Voltage
- Symmetrical 25ns read and write timing
- Bit Cell Size = 1.55µm$^2$
- Die Size 4.5 x 6.3mm

Proc. IEEE International Electron Devices Meeting 2003
Proc. Intermag 2004, IEEE Trans. Mag., in press.
Proc. ISSCC 2004

# 4Mb MRAM Bit Cell

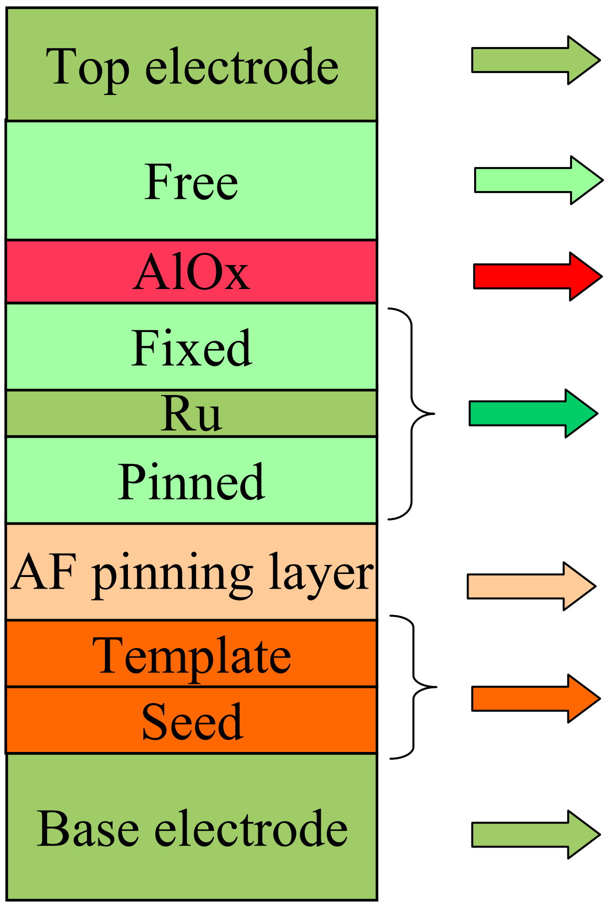
Sense path electrically isolated from program path



# Magnetic Tunnel Junction Material

# Full MTJ Stack for MRAM

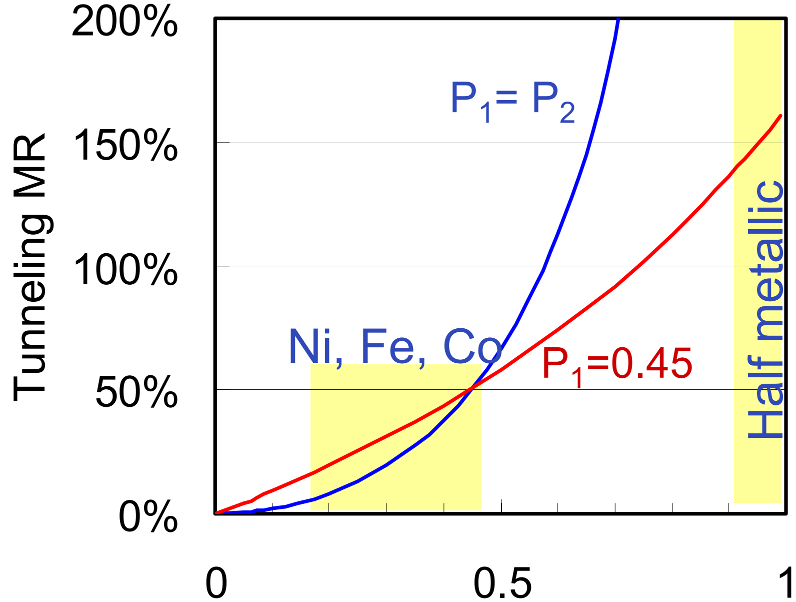
Full MTJ Stack
for MRAM




- Top electrode: Low resolution contact
- Free: Switches between two magnetic states in applied field. Stores information.
- AlOx: Tunnel barrier. Affects resistance and MR ratio.
- Fixed / Ru / Pinned: Synthetic Antiferromagnet (SAF). AF coupling through Ru layer makes the structure stable in applied magnetic fields. Relative thickness of Fixed and Pinned used to center loop.
- AF pinning layer: Pins the bottom magnetic layers.
- Template / Seed: Seeds growth, determines crystal structure
- Base electrode: Low resistance contact

# Effect of Increasing Polarization

Signal (MR) increase with polarization of electrodes




One half-metallic electrode would give a huge signal boost for MRAM

Recent reports of high TMR with crystalline MgO barrier indicate potential for similar effect.

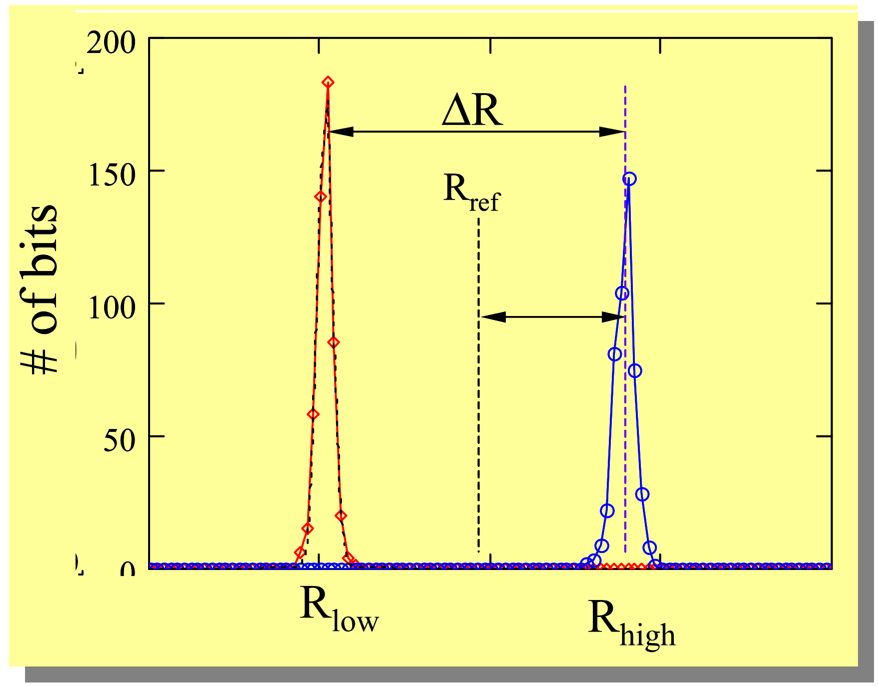
Increase in signal would
- relax requirements on R distributions
- provide higher speed
- enable alternate architectures

Finding a high-polarization material system that can be applied commercially is a huge challenge and huge opportunity!

# Reading from an array

# High MR is Not Enough

Array: $R_{cell}$ Histogram




$MR = \Delta R/R_{low}$ , $\Delta R = R_{high} - R_{low}$

**Signal = $R_{cell} - R_{ref}$**

- **½ of ΔR available for sensing**

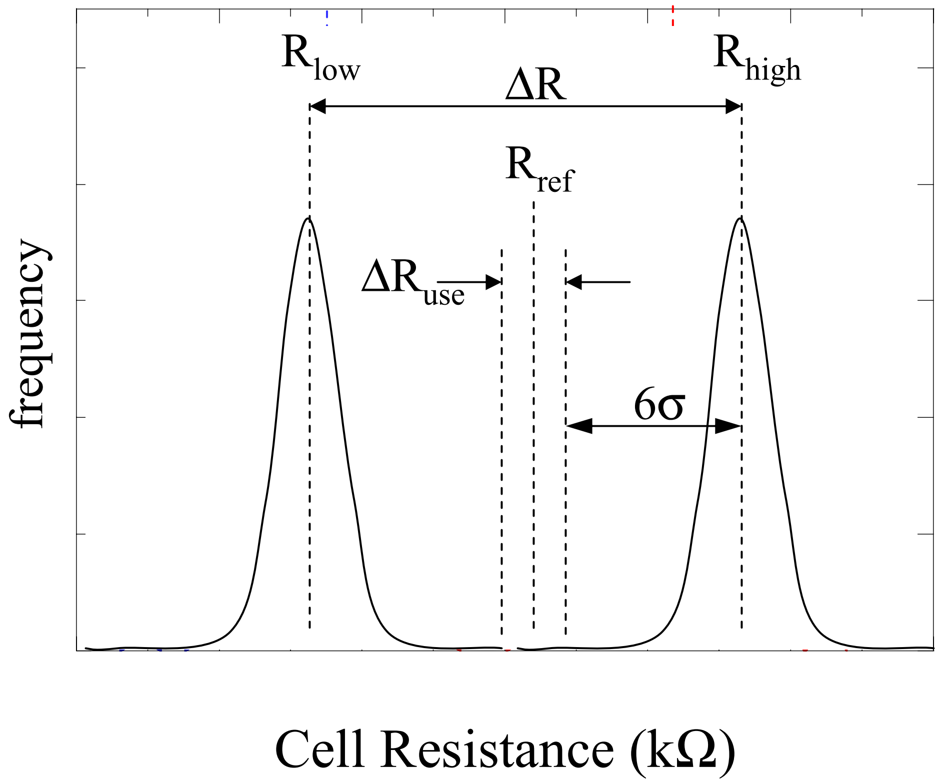
**Circuit works at finite bias**

- **MR is reduced by bias dependence of MR**

**Must sense all bits in the array**

- **Circuit must work with bits in tails of the R distribution**

# Resistance Variation In Array




Resistance distribution reduces useable MR.

For six-sigma yield in the array, need:
$\Delta R/2 > 6\sigma$

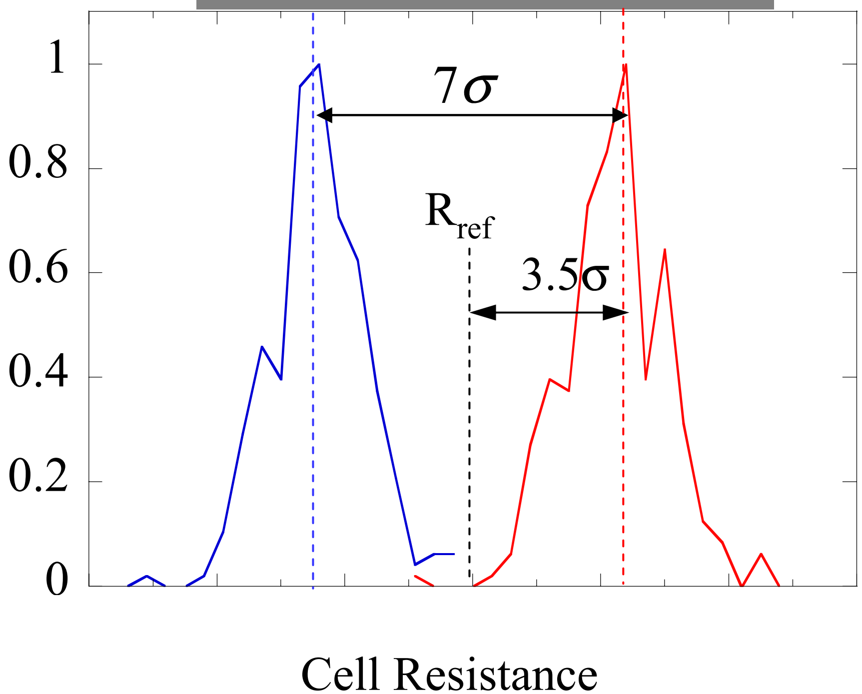
NOT related to wafer-level uniformity

RA=10.4 kΩ-μm$^2$, $\sigma$=6%

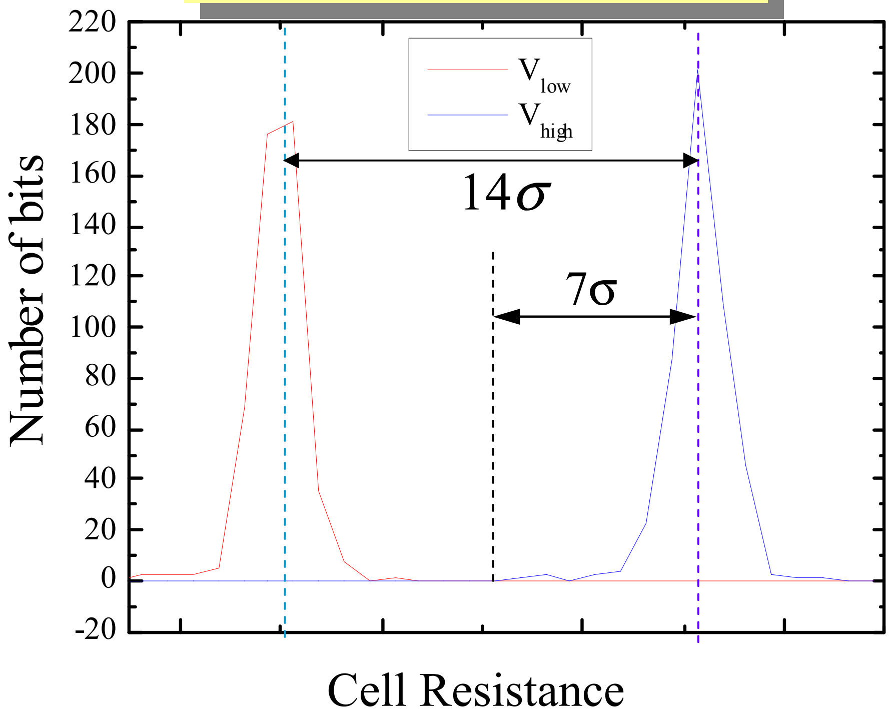
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 11.3 | 11.0 | 10.5 | 10.5 | 10.9 | 12.3 | |
| 11.7 | 10.3 | 9.74 | 9.88 | 9.65 | 9.80 | 10.2 | 11.5 |
| 10.3 | 9.54 | 10.9 | 10.6 | | 10.3 | 9.74 | 10.5 |
| 10.1 | 9.68 | 10.4 | 10.8 | 10.8 | 10.7 | 9.85 | 10.7 |
| | 9.80 | 10.9 | 10.5 | 10.8 | 10.5 | 9.86 | 10.2 |
| 10.3 | 9.45 | 10.1 | 10.4 | 10.6 | 9.87 | 9.62 | 10.9 |
| | 10.2 | 9.52 | 9.43 | 9.56 | 9.59 | 10.2 | |
| | | 11.2 | 10.2 | 10.4 | 11.0 | | |

# Resistance Uniformity Within Array

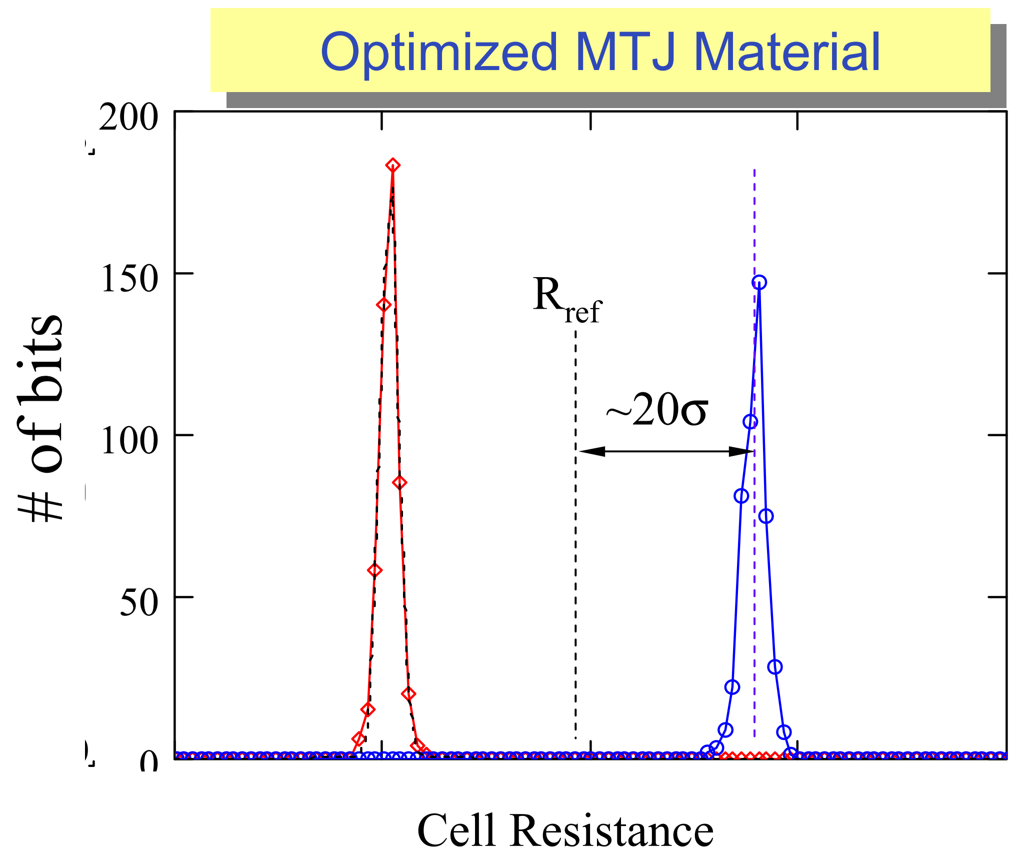
Common MTJ Material




Improved MTJ Material



# Resistance Distribution Within Array



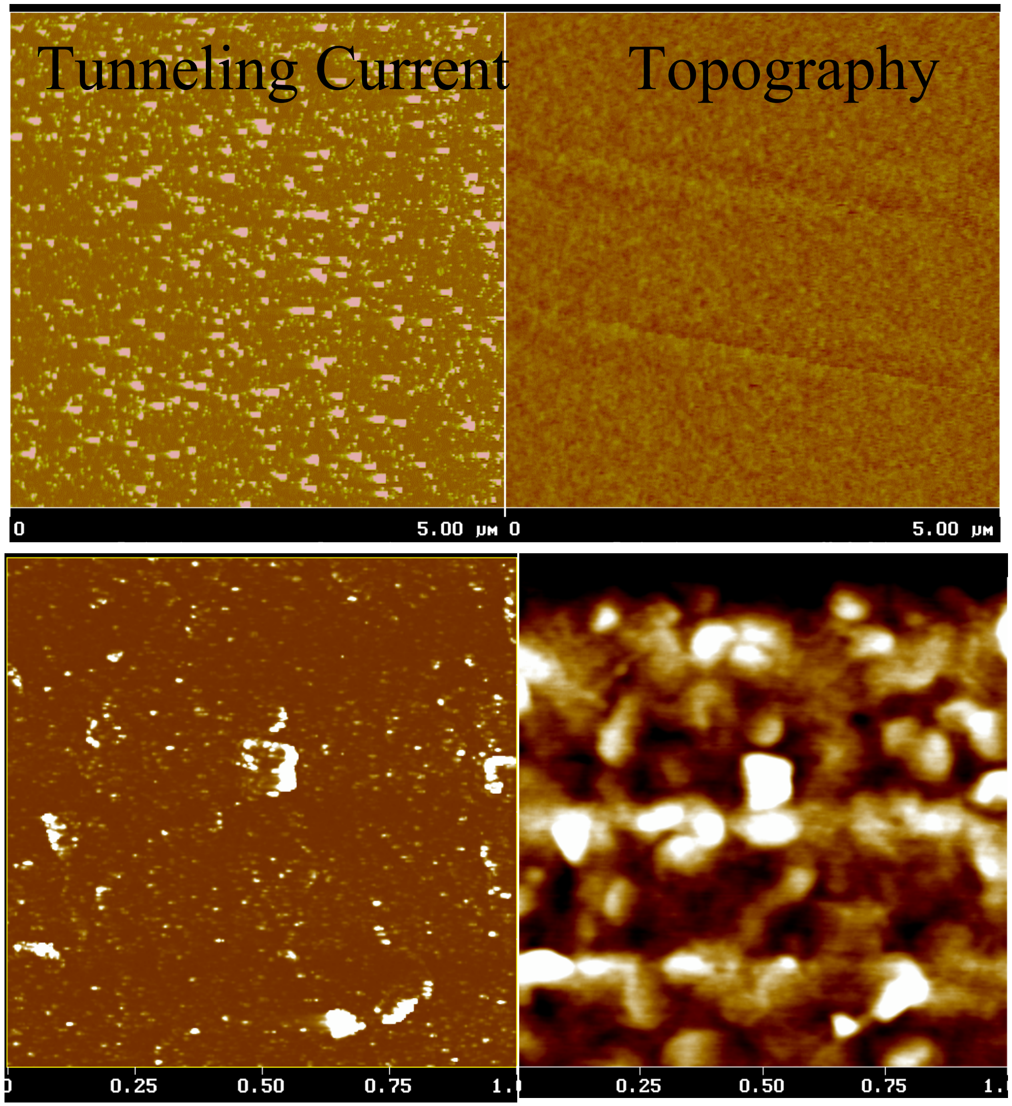

High MR and narrow RA distribution:
~20σ margin on read

- Distribution width < 1%
- MR(at bias) ≈ 30 %

Other possible contributors to distribution widths:

- Lithography
- Etching
- Process damage

# Tunneling AFM Measurements of Barrier Uniformity



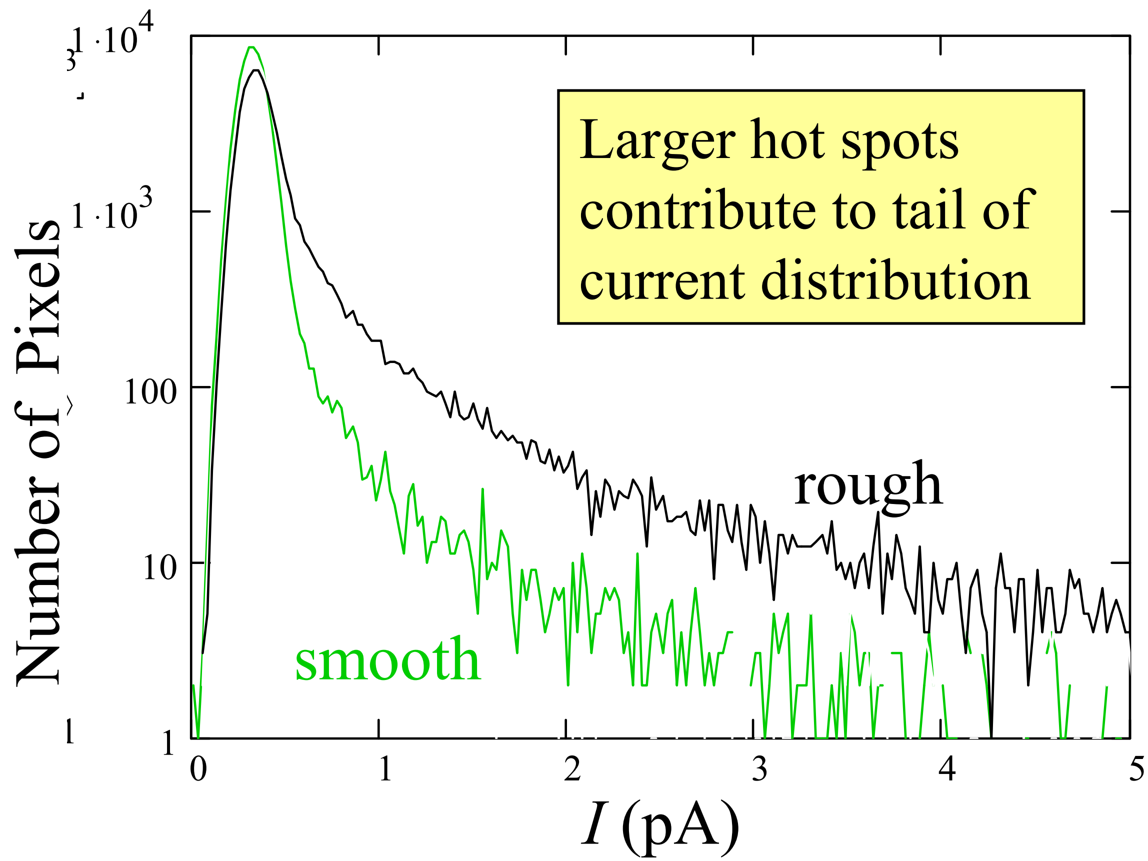

smooth — $5\mu m \times 5\mu m$

rough — $1\mu m \times 1\mu m$

Jon Slaughter, ANL/APS Nanomagnetism Workshop, 31August, 2004

Launched by Motorola freescale semiconductor

# Current histogram: Tunneling AFM




**Comparative analysis**

- Follows log-normal distribution
- $\sigma$ is figure of merit
- Control more difficult for lower RA and smaller bits

Research Opportunity:
Insulating material with lower barrier height would allow thicker barriers for low RA material.  Many materials requirements to meet.

# High MR is Not Enough

## High MR materials are valuable if tunnel barrier quality is maintained

- Figure of merit for read is $\Delta R/\sigma$
- Ideal improved material would provide increased MR with same $\sigma$
- Roughness and interface quality just as important as ‘polarization’

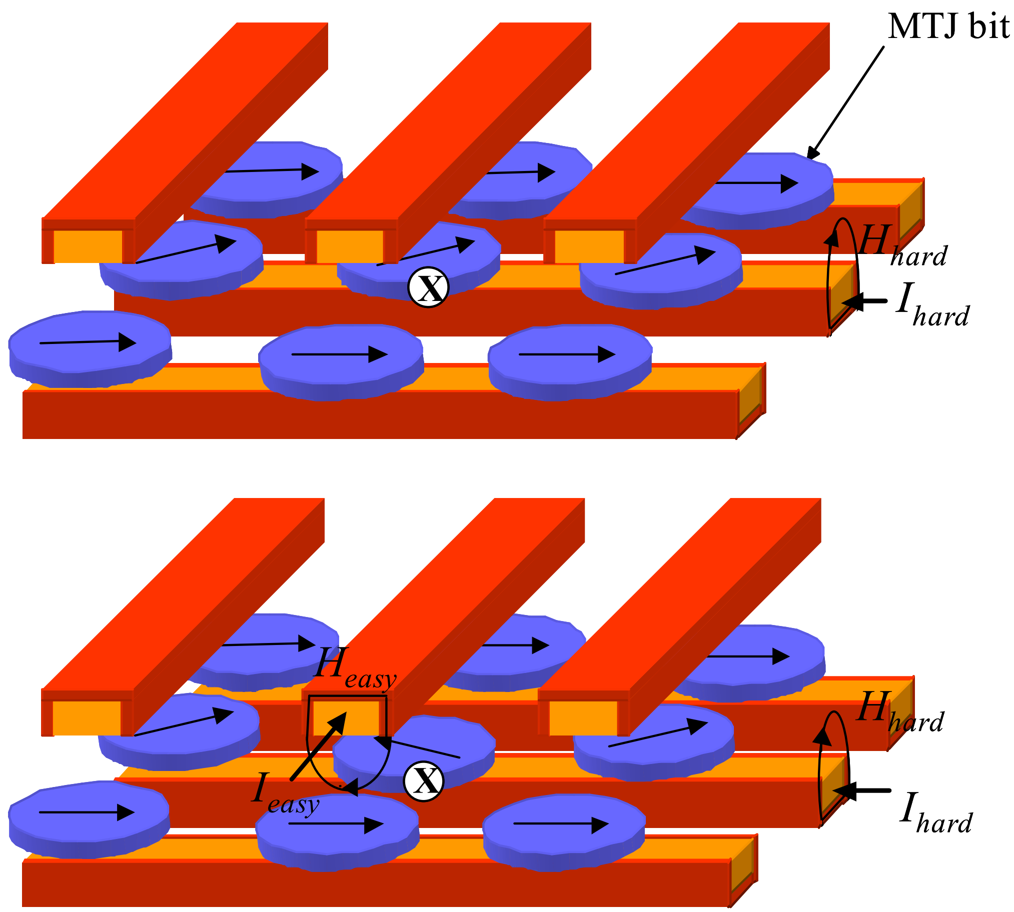
# Opportunities in MTJ Material

## Improved MR/$\sigma$

- **High polarization materials for the tunneling electrodes**
  - Proof of half-metallicity or high polarization (e.g. is $Fe_3O_4$ really ½ metallic?)
  - Stability of the interface with tunnel barrier
- **Tunnel barrier materials (e.g. AlOx & MgO)**
  - Growth and interface studies
  - Stability: e.g. migration of atoms under thermal or electrical stress
- **Electrode/barrier combinations**
  - Smoothness of interfaces
  - Control of tunneling hot spots on small scale
  - Practical process for deposition/growth:  what materials have the most promise for applications?

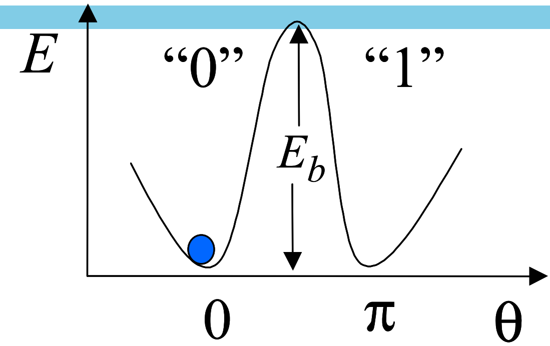
# Writing bits in an array

# Conventional MRAM:  Bit Selection



# Energy Barrier Model of Magnetization Reversal

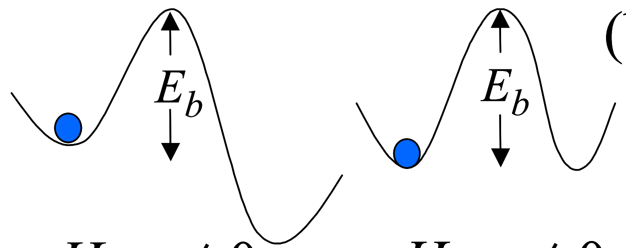
Unselected




(a) $H = 0$

½-Selected

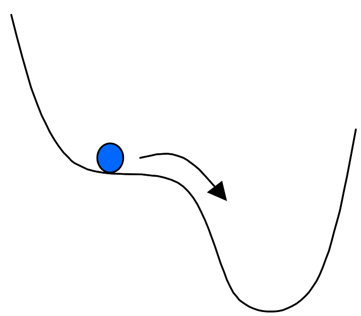
*Lower barrier*




$H_{easy} \neq 0$ $\quad$ $H_{hard} \neq 0$

(b) $H_{easy} \neq 0$ or $H_{hard} \neq 0$

Selected



(c) $H_{hard} \neq 0$ and $H_{easy} \neq 0$

# New Writing Approach: "Savtchenko Switching"

**Proposed at Motorola by the late Leonid Savtchenko**

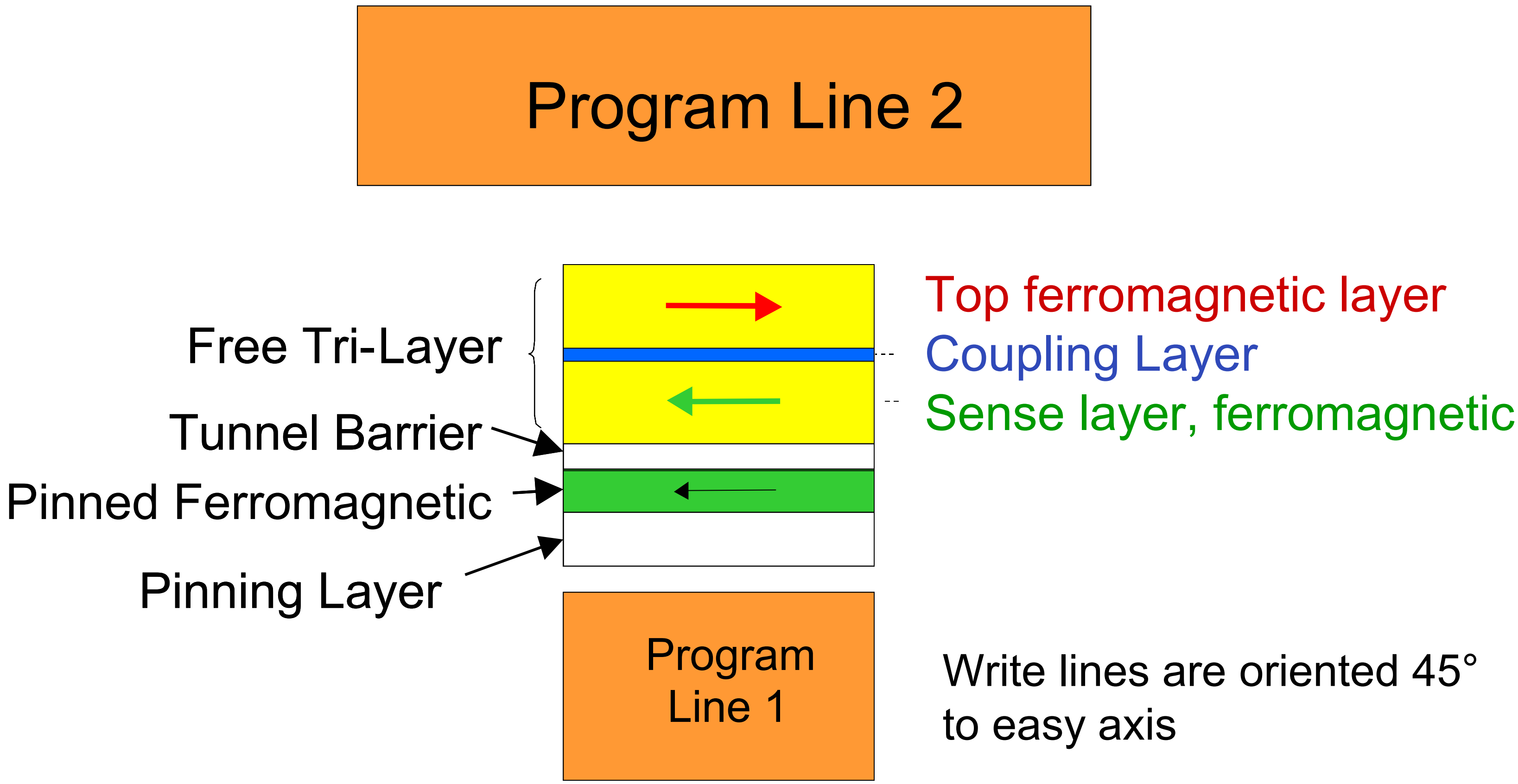
- **US Patent 6,545,906**

**Write operation is a rotation of a balanced SAF**

**Toggle rather than "forced" write**

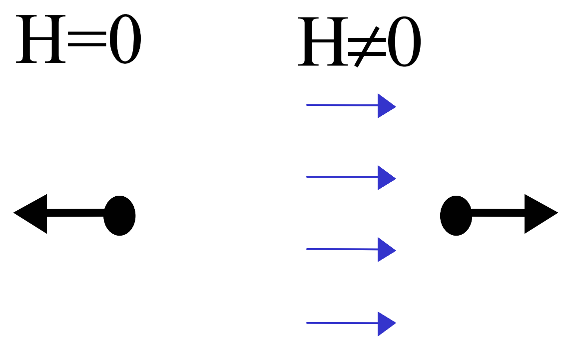
Leonid Savtchenko

# Toggle MRAM Bit Cell

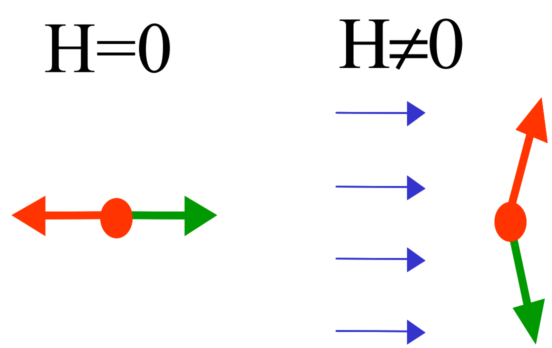


# Free Layer Field Response

## Conventional Free Layer

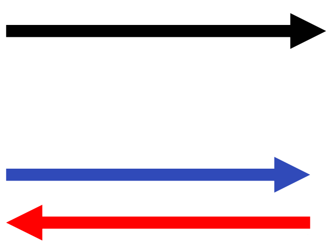



## Tri-Layer Coupled Free layer



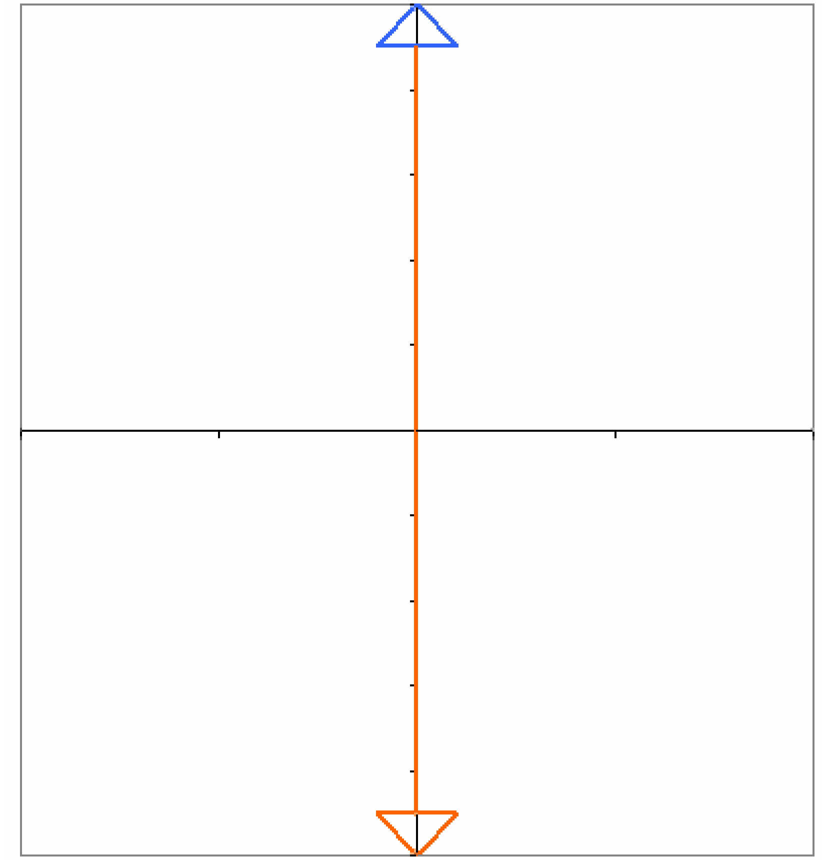
# Single Domain Switching Model

- Balanced NiFe SAF free layer
- Write lines 45° to easy axis
- Unipolar currents, $\tau_p \approx 6$ ns



= H

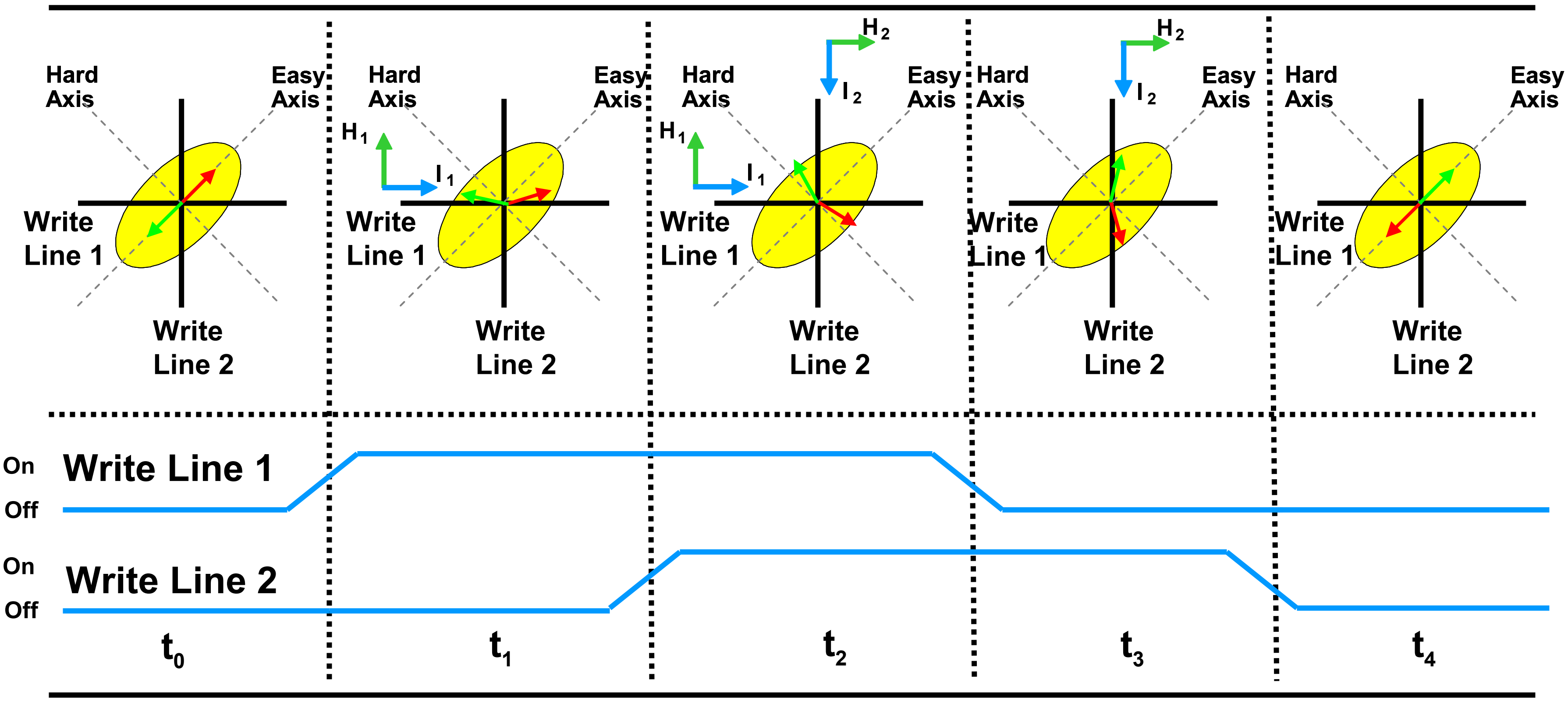
= M



$$H_{sw}^{1,2} = \sqrt{\frac{H_k \cdot H_{sat}}{2}}$$

$H_k$ = anisotropy field
$H_{sat}$ = SAF saturation

# Toggle MRAM Switching Sequence



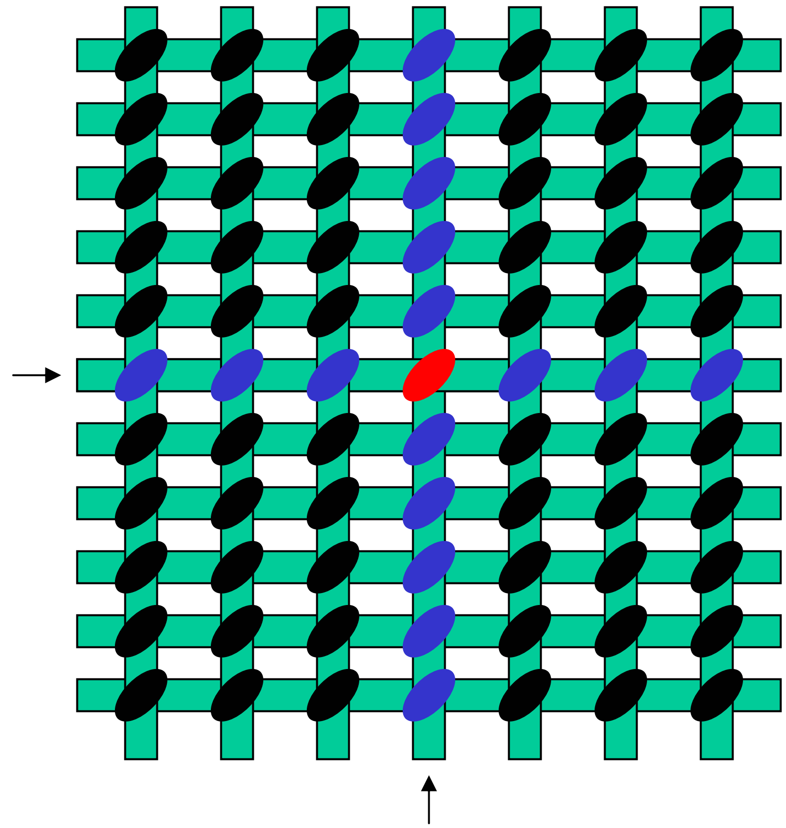

Unipolar currents

Overlapping pulse sequence

Pre-read / decision write

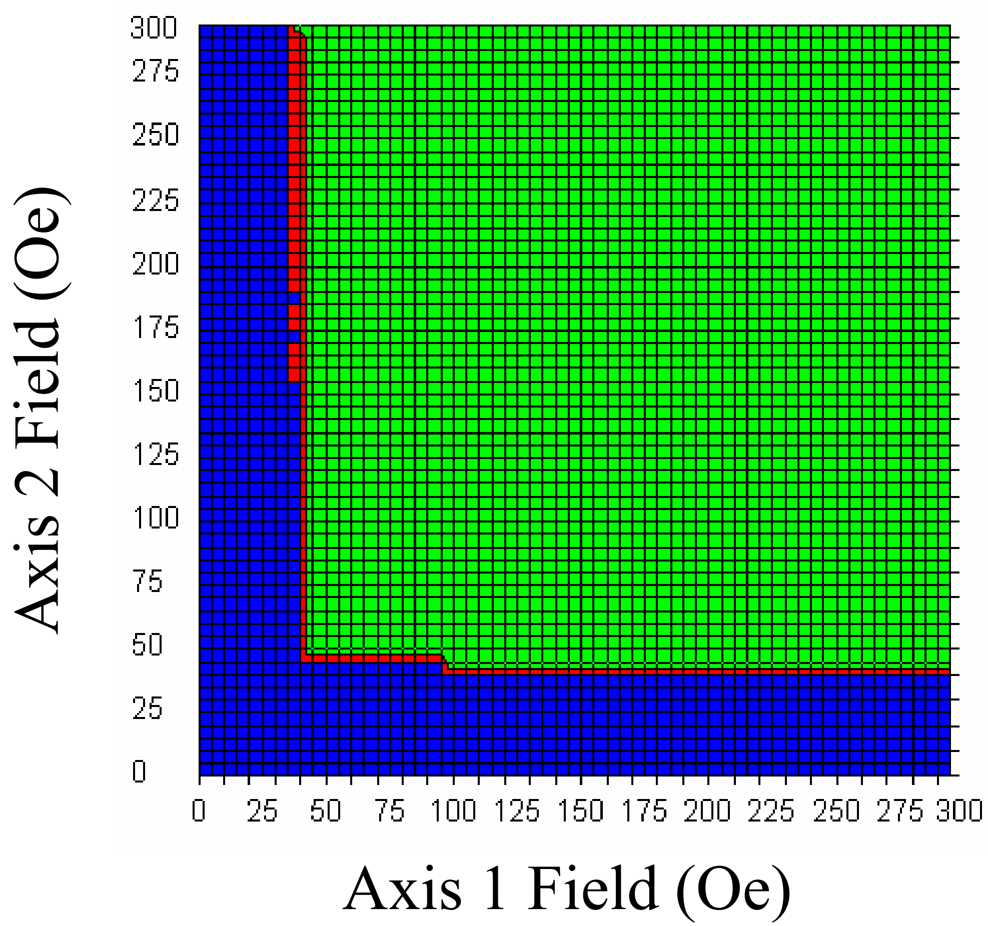
# Toggle-Bit Selection

- High bit disturb margin
- All bits along ½-selected current lines have ***increased*** energy barrier during programming
- Requires overlapping pulse sequence for switching

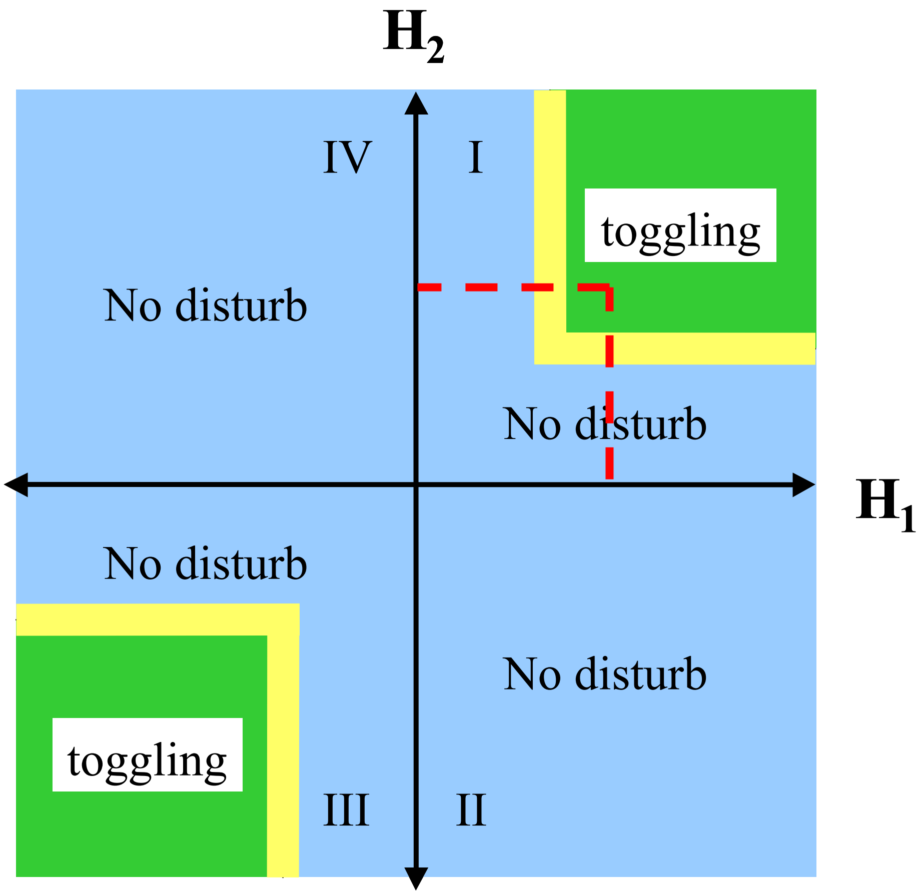


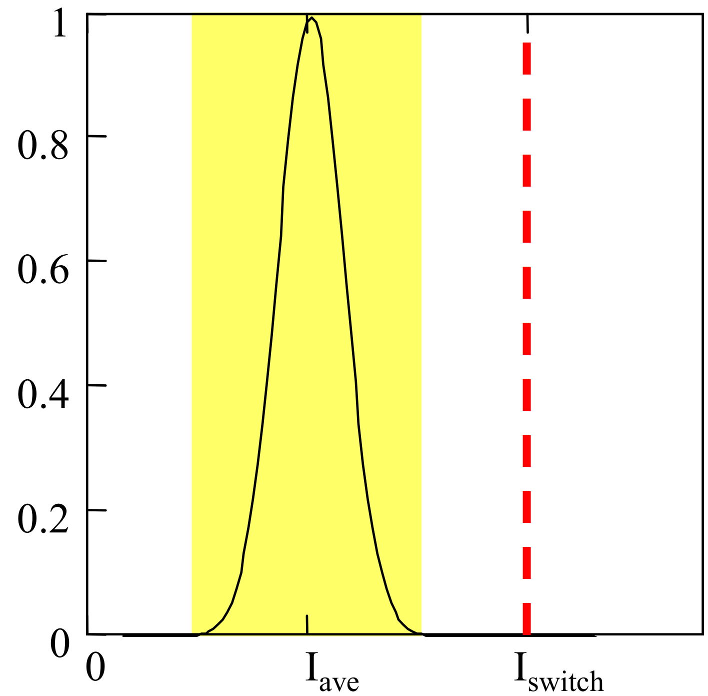
# Measured Single Bit Switching

## No disturb to > 300 Oe!

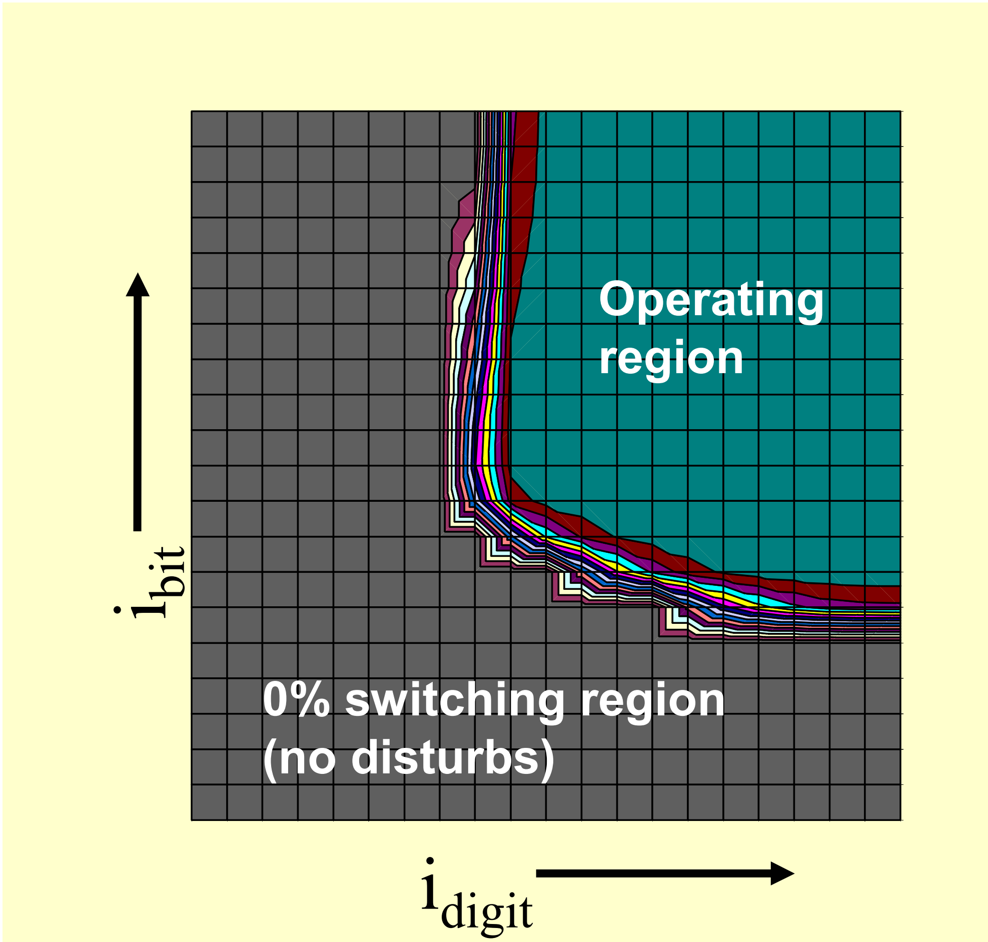


# Toggle-Bit Array Characteristics



# Measured Switching from 4Mb Toggle-MRAM



# Opportunities in bit switching

**The Savtchenko approach enables switching of bits with competitive sizes, within large arrays.**

**Innovations that would improve performance and assist in scaling to smaller dimensions include:**

- **Fundamental understanding of switching dynamics and origin of switching distributions.**
- **Materials with high polarization and well-behaved permalloy-like magnetic properties**
- **Other devices that allow decreased switching current without thermal disturb**
- **Alternate switching approaches**
  - Is there something better than Savtchenko at smaller dimensions?  (SMT?)
  - What are the engineering tradeoffs of the alternatives?

# Summary

**A 4Mb MRAM integrated into a 0.18μm CMOS process has been successfully demonstrated for the first time.**

- MTJ optimized for read. Toggle writing scheme

**Read: High quality, smooth, tunnel junctions are critical**

- High MR is necessary but not sufficient
- Bit-to-bit resistance distributions and bias dependence of MR are critical
- Opportunities: higher polarization materials, improved tunnel barriers, band structure engineering?

**Write: Toggle writing with balanced SAF enables current technology**

- Improves: disturbs, operating window, data retention, scaling
- Opportunities: improved materials or alternate devices that can switch with less current, without sacrificing data retention, etc.

# Photon-based methods

## Materials Studies

- **Chemical and magnetic roughness, spin & orbital moments**
  - X-ray resonant magnetic scattering (XRMS)
  - X-ray magnetic circular dichroism (XMCD)
- **Best way to study interface sharpness, stability?**
- **Best test to prove or disprove ½ metals?**

## Magnetic Imaging

- **Domains, direction of moment in bits, element-specific studies**
  - Photoemission microscopy (PEEM)
  - Scanning transmission x-ray microscope (STXM)
- **Deep submicron resolution necessary to study micromagnetics of bit switching**
- **Time-resolved on the ns scale or below needed to observe bit switching**